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TECHNICAL REPORT

Publicly Released Prompt Radiation Spectra Suitable for Nuclear Detonation Simulations

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March 2017

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement[*]

U.S. Customary Units	**Multiply by →**	**← Divide by[†]**	**International Units**
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
atomic mass unit (AMU)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electronvolt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
Erg	1	$\times 10^{-7}$	joule (J)
kiloton (kT) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^{3}$	pascal (Pa)
Temperature			
degree Fahrenheit (ºF)	[T(ºF) − 32]/1.8		degree Celsius (ºC)
degree Fahrenheit (ºF)	[T(ºF) + 459.67]/1.8		kelvin (K)
Radiation			
curie (Ci) (activity of radionuclides)	3.7	$\times 10^{10}$	s^{-1}[‡]
air exposure (roentgen)	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
absorbed dose (rad)	1	$\times 10^{-2}$	J kg^{-1}[§]
equivalent and effective dose (rem)	1	$\times 10^{-2}$	J kg^{-1}[**]

[*] Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.

[†] Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

[‡] The special name for the SI unit of the activity of a radionuclide is the becquerel (Bq). (1 Bq = 1 s^{-1}).

[§] The special name for the SI unit of absorbed dose is the gray (Gy). (1 Gy = 1 J kg^{-1}).

[**] The special name for the SI unit of equivalent and effective dose is the sievert (Sv). (1 Sv = 1 J kg^{-1}).

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Executive Summary

This technical report contains a set of neutron and photon spectra that can be used for simulating the prompt radiation from a nuclear device or weapon in a radiation transport model. Applied Research Associates, Inc. (ARA) collected these weapon outputs to improve simulations of the prompt radiation of nuclear devices though complex urban environments. The simulations are for emergency planning, consequence assessment, and medical countermeasure development by the civilian community.

After listing eleven different sets of data, this technical report suggests that four sets of neutron and photon spectra are the most suitable for simulations: the two sets of spectra from Hiroshima and Nagasaki fission weapons and two sets of spectra from DNA 4267F. These were chosen by the authors due to the relative completeness of their quantitative description.

1 Introduction

As part of its mission to safeguard against weapons of mass destruction (WMD), the Defense Threat Reduction Agency (DTRA) supports the development of capabilities to reduce, eliminate and counter WMD threats and mitigate their effects. Applied Research Associates (ARA) was tasked by DTRA to support this mission by providing publicly available nuclear detonation radiation spectra essential for the civilian community in emergency planning, consequence assessment, and medical countermeasure development. This technical report describes different unclassified leakage spectra that can be used to simulate a nuclear device or weapon in a radiation transport model.

ARA has developed capabilities to simulate the prompt radiation of nuclear devices in a three-dimensional Monte Carlo radiation transport model. These models include 3-D representation of urban geometries complete with internal structure and external walls. ARA uses the models to improve consequence assessment analysis to help inform nuclear terrorism response planning communication to the public but respects the sensitive nature of nuclear weapon effects simulations. This technical report describes various prompt radiation spectra and attempts to sort out the ones that can be both meaningful representations of possible devices and are also available for public release.

An associated spreadsheet is available with this technical report that provides numerical data sets to support radiation transport modeling.

2 Description of Prompt Radiation Spectra

The prompt radiation spectrum is the neutron and photon radiation released in the short time, much less than a microsecond, after detonation (Glasstone, 1977). The detonation releases both neutron and photons in this time; however, the neutron emission dominates the photon emission. During the Hiroshima and Nagasaki bombings, the prompt radiation contributed from 40%-70% of the free-in-air dose depending on distance from epicenter (Young, R.W. & Kerr. G.W. [Eds.], 2005). Some of the leakage spectra for the photon spectrum listed are not available or contain more sensitive information than the neutron spectrum. Table 1 lists various spectra that are available. Note, all the spectra listed are unclassified.

Table 1 - List of unclassified spectra

Source	*Description*	*Both Neutron and Photon Spectra?*
White, Whalen & Heath 2001 (Little Boy)	Analysis of ^{235}U Hiroshima fission weapon	Yes
White, Whalen & Heath 2001 (Fat Man)	Analysis of ^{239}Pu Nagasaki fission weapon	Yes
Whalen 1983 (Little Boy)	Analysis of ^{235}U Hiroshima fission weapon	Yes
Whalen 1983 (Fat Man)	Analysis of ^{239}Pu Nagasaki fission weapon	Yes
Glasstone & Dolan 1977 (Fission)	Neutron fission spectrum from “The Effects of Nuclear Weapons”	No
Glasstone & Dolan 1977 (Thermonuclear)	Neutron spectrum from thermonuclear device from “The Effects of Nuclear Weapons”	No
Terrell 1990	MCNP calculation of idealized Godiva device	Yes
Kaul & Egbert 2000	Neutron spectrum from unshielded Army Pulse Reactor Division reactor	Yes
Auxier, et al. 1972 (Low, Intermediate, High)	Suggested neutron spectra for high-, intermediate- and low-yield thermonuclear weapons for initial radiation shielding calculations	No
Gritzner, et al. 1976 (EM-1, Low, Henre)	Source spectra from potential tactical nuclear weapons and the Henre experiment	Yes
Barnes, et al. 1991	Estimated spectrum for a boosted fission weapon	No

3 Discussion of Spectra

There are four categories of neutron spectra presented: "Little Boy", "Fat Man", unshielded or bare sphere, and thermonuclear. "Little Boy" is a gun-assembled weapon while "Fat Man" is a high-explosive assembled weapon, but since there aren't other similar spectra in the public domain, the authors will refer to them by their names. The Radiation Effects Research Foundation (RERF) has extensively modeled the "Little Boy" and "Fat Man" weapon spectra from the Hiroshima and Nagasaki nuclear detonations, respectively, and the radiation spectra are fairly detailed (Young, R.W. & Kerr. G.W. [Eds.], 2005). However, the differences between the two spectra show the sensitivity of these devices to their design. The old 1986 analyses of "Little Boy" and "Fat Man" are not shown in the plots since it has been made obsolete by the 2001 report by White, Whalen and Heath. The spectra for "Little Boy" are known to have a significant angular dependence; however, for the applications of emergency planning, consequence assessment, and medical countermeasure development isotropic sources are more suitable. The isotropic, angular-average version of the spectrum is plotted in this report and provided in the accompanying spreadsheet. A 2013 LANL report (Holmes and White, 2013) presents a new look at the "Little Boy" and "Fat Man" outputs, but the published output spectra did not change from the 2001 LANL report.

The Glasstone & Dolan 1977 fission spectra is a calculation of a bare sphere undergoing ^{235}U fission. Glasstone & Dolan 1977 includes a thermonuclear spectrum as well. The APRD (the Army Pulse Radiation Division) report (Kaul and Egbert, 2000) contains a calculation based on experimental data from an unshielded reactor. The Terrell report details an MCNP (Monte Carlo N-Particle radiation transport code) calculation of an idealized Godiva device with 93.77% ^{235}U. The Oak Ridge report (Auxier, et al., 1976) includes three "typical" thermonuclear neutron spectra created from transport calculations and suggests the intermediate one (300 kT) as the standard. A second Oak Ridge report (Barnes, et al. 1991) contains an estimated neutron spectrum for a boosted fission device. The Defense Nuclear Agency report 4267F (Gritzner, et al., 1972) contains three source spectra: an unshielded fission source, a thermonuclear spectrum from a hypothetical low-yield weapon and a spectrum from the reactor employed in the Henre experiment.

All the fission neutron spectra identified in Table 1 are plotted in Figure 1. Figure 2 is the same plot, but showing only the neutron energies above 0.1 MeV. Figure 3 shows the thermonuclear neutron spectra with Figure 4 showing the same, but with the domain again limited to neutron energies above 0.1 MeV. Figure 5 shows the available primary photon spectra for the corresponding fission sources. Figure 6 shows the primary photon spectra for the two thermonuclear spectra in DNA 4267F.

Each data set has its own method of binning particle energy; therefore, for purposes of comparison, each histogram bin is divided by the difference in energy between bin divisions. The authors used total neutrons per kT for normalization. However, data sets are frequently published as unnormalized fractions. In those cases, the authors of this report used neutrons (or photons) per kT from one of the Glasstone spectra or from one of the DNA 4267F spectra. The normalizations are listed in Table 2.

The authors extracted the total number of neutrons per kT for both of the Glasstone & Dolan 1977 spectra by digitizing the plots in Figure 8.116a and Figure 8.116b of Glasstone & Dolan 1977 and summing the values of each histogram bin. This quantity is only used for comparison.

The details of each spectrum are contained in a spreadsheet which is available on request.

Table 2. Total number of particles used for plotting

Source Spectra	Particle Type	Source	Total Particles per kT for comparison normalization
Little Boy	Neutron	White, Whalen & Heath 2001	1.065×10^{23}
Fat Man	Neutron	White, Whalen & Heath 2001	1.590×10^{23}
APRD reactor	Neutron	Glasstone & Dolan 1977	7.760×10^{22}
Glasstone (Fission)	Neutron	Glasstone & Dolan 1977	7.760×10^{22}
Terrell	Neutron	Glasstone & Dolan 1977	7.760×10^{22}
DNA 4267F (EM-1 Fission)	Neutron	Gritzner, et al. 1976	1.00×10^{23}
Glasstone (Thermonuclear)	Neutron	Glasstone & Dolan 1977	1.445×10^{23}
ORNL-TM-11775 (Boosted Fission)	Neutron	Barnes, et al. 1991	3.102×10^{23}
ORNL-TM-3396 (High Yield Thermonuclear)	Neutron	Glasstone & Dolan 1977	1.445×10^{23}
ORNL-TM-3396 (Intermediate Yield Thermonuclear)	Neutron	Glasstone & Dolan 1977	1.445×10^{23}
ORNL-TM-3396 (Low Yield Thermonuclear)	Neutron	Glasstone & Dolan 1977	1.445×10^{23}
DNA 4267F (Low Yield Thermonuclear)	Neutron	Gritzner, et al. 1976	2.00×10^{23}
DNA 4276F (Henre)	Neutron	Gritzner, et al. 1976	1.00×10^{24}
Little Boy	Photon	White, Whalen & Heath 2001	4.014×10^{21}
Fat Man	Photon	White, Whalen & Heath 2001	7.287×10^{22}
Terrell	Photon	Gritzner, et al. 1976	3.00×10^{22}
APRD reactor	Photon	Gritzner, et al. 1976	3.00×10^{22}
DNA 4276F (EM-1 Fission)	Photon	Gritzner, et al. 1976	3.00×10^{22}
DNA 4276F (Low Yield Thermonuclear)	Photon	Gritzner, et al. 1976	7.0×10^{22}
DNA 4276F (Henre)	Photon	Gritzner, et al. 1976	1.0×10^{23}

4 Conclusions on Use of Spectra

The suggested spectra for use in simulations of prompt radiation from nuclear devices intended for public release are shown in Table 3. The authors chose these spectra because of the resolution and range, possessing information about source particles per kT normalizations and having a corresponding primary photon spectrum.

Table 3. Suggested spectra for simulation of leakage radiation for a nuclear device

Type of Spectrum	Neutron Source	Photon Source
"Little Boy"-type spectrum	White, Whalen & Heath 2001	White, Whalen & Heath 2001
"Fat Man"-type spectrum	White, Whalen & Heath 2001	White, Whalen & Heath 2001
Unshielded device spectrum	Gritzner, et al. 1976 (EM-1 Fission)	Gritzner, et al. 1976 (EM-1 Fission)
Thermonuclear spectrum	Gritzner, et al. 1976 (Low Yield Thermonuclear)	Gritzner, et al. 1976 (Low Yield Thermonuclear)

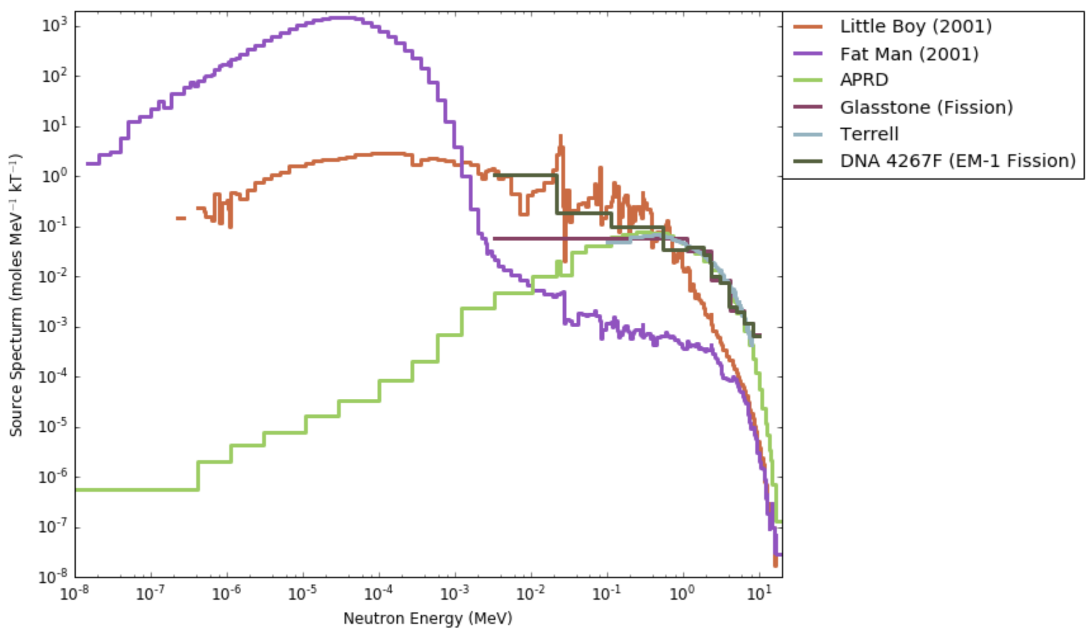

Figure 1. Neutron spectra from fission sources

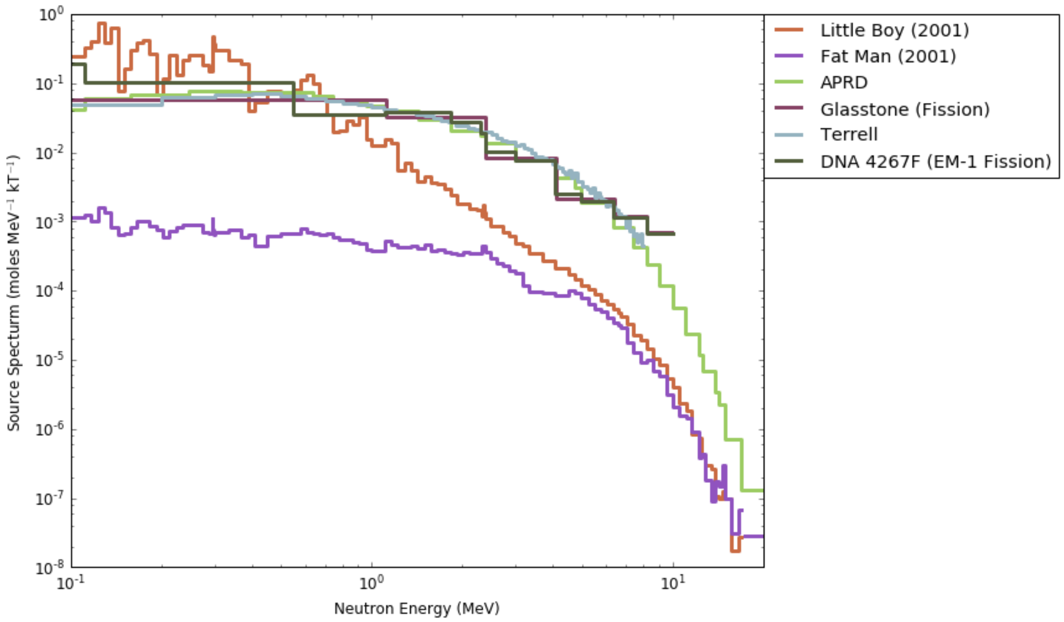

Figure 2. Fission neutron spectra with values greater than 0.1 MeV

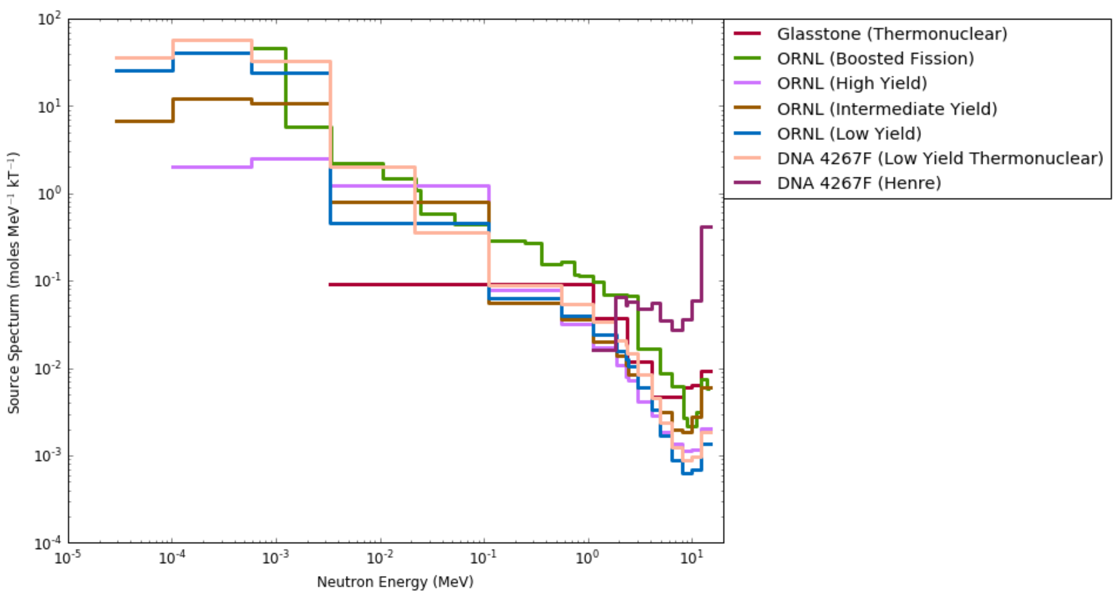

Figure 3. Neutron spectra from thermonuclear sources

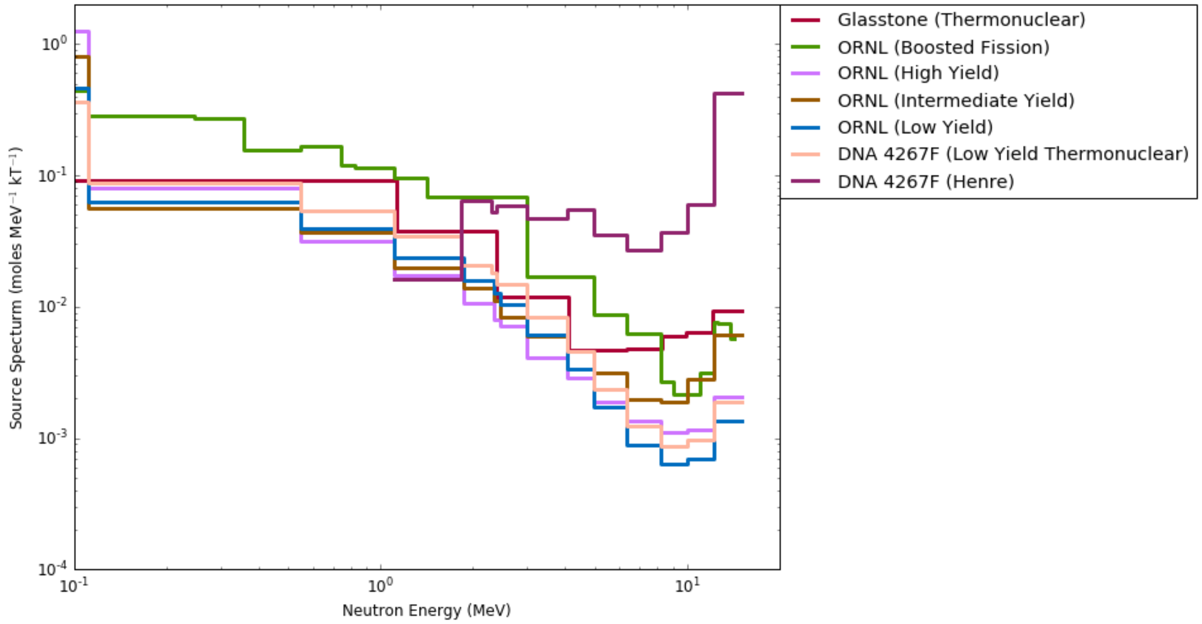

Figure 4. Thermonuclear neutron spectra with energies greater than 0.1 MeV

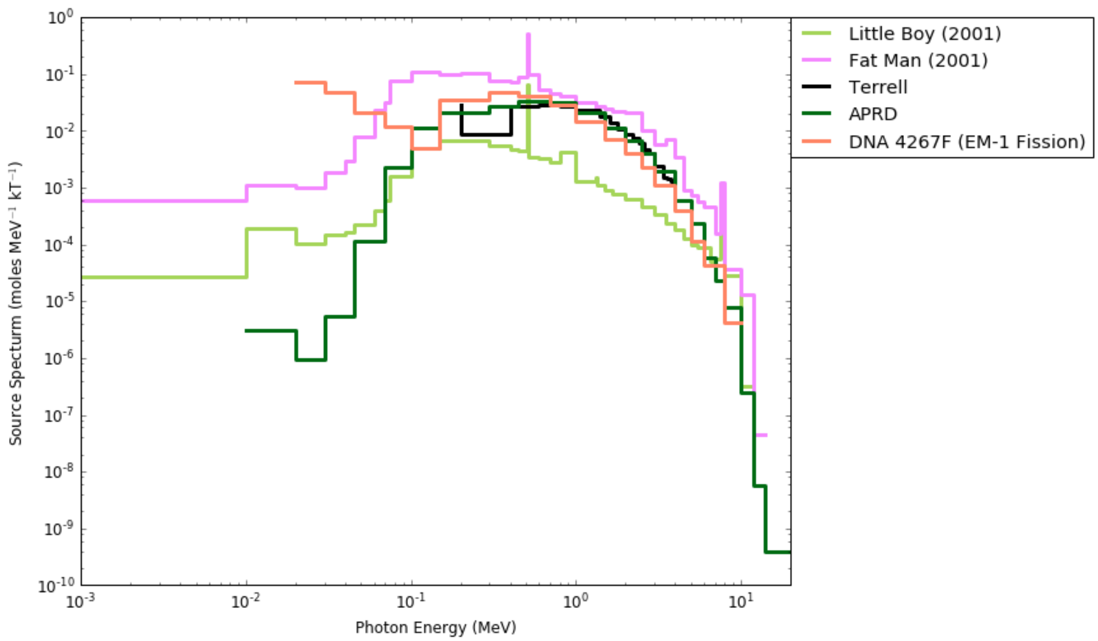

Figure 5. Photon spectra from fission sources

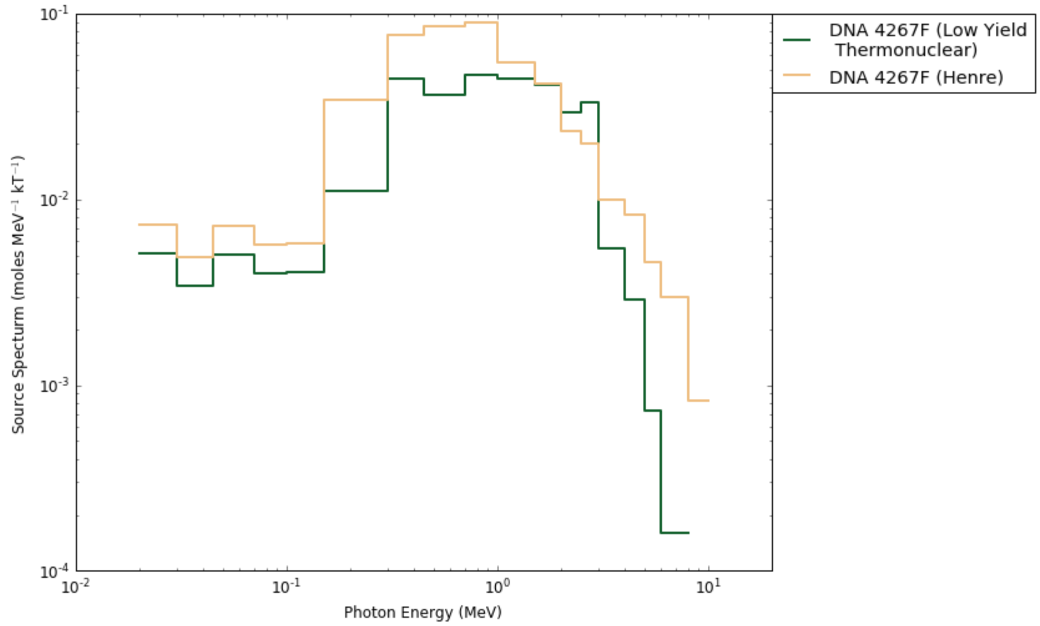

Figure 6. Photon spectra from thermonuclear sources

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Abbreviations, Acronyms, and Symbols

ARA	Applied Research Associates, Inc.
APRD	Army Pulse Reactor Division
ATR6	Air-Transport of Radiation Version 6
DNA	Defense Nuclear Agency
DS02	Hiroshima and Nagasaki Dosimetry System 2002
DTRA	Defense Threat Reduction Agency (United States)
HSRD	Human Survivability Research and Development Integrated Program Team
EM-1	Effects Manual volume 1
FOUO	For Official Use Only
IPT	Integrated Program Team
kT	Kiloton
MCNP	Monte Carlo N-Particle radiation transport software
mole	A number of constituent particles equal to the Avogadro constant (6.022×10^{23})
ORNL	Oak Ridge National Laboratories
RERF	Radiation Effects Research Foundation
TR	Technical Report
U.S.	United States
WMD	Weapons of Mass Destruction